

From Architectural Design to Structural Analysis: A Data-Driven Approach to Study Building Information Modeling (BIM) Interoperability

Mohammed Aldegeily[1], Yufeng Hu, Ph.D., P.E.[3] and Xiaoyun Shao, Ph.D., PE[3]
Western Michigan University,
Kalamazoo, MI[1,3]

Jiansong Zhang, Ph.D.[2]
Purdue University,
West Lafayette, IN[2]

Building Information Modeling (BIM) has been playing an essential role in building construction projects in recent years. It was used to automate many tasks such as cost estimation and structural analysis. However, BIM interoperability is still lacking in many fields across the architecture, engineering, and construction (AEC) domain. This paper studies the interoperability between architectural design and structural analysis. The goal is to explore BIM-based structural analysis through data transfer between different software via three types of paths: (1) direct link using native file, which is the direct link between software programs from the same provider; (2) direct link using application programming interface (API), which is the direct data transfer with a BIM platform through its APIs; and (3) indirect link, which is the indirect transfer of information through third party software or methods/algorithms, with a particular focus on the use of industry foundation classes (IFC) data. IFC is an ISO-registered, open and neutral data exchange standard for BIM. Although IFC was designed to be comprehensive in supporting all disciplines and phases of a building construction project, the authors found that IFC exports from architectural design software usually lack essential information elements needed for structure analysis such as loads information.

Key Words: Building Information Modeling (BIM), Industry Foundation Classes (IFC), Interoperability, Architectural Design, Structural Analysis.

Introduction

Architectural design and structural analysis are two different domains that are closely related to a construction project. Both fields have separate procedures with distinguished objectives in a building construction project. Architectural design defines the configurations of different architectural elements such as their dimensions and materials, whereas structural analysis analyzes the structural and mechanical properties of building elements such as stress, strain, and stability (Chen et al., 2005). Both architectural design and structural design play essential roles in the successful design and construction of a building.

Building information modeling (BIM) has been an emerging trend in the architecture, engineering, and construction (AEC) domain. One main advantage of utilizing BIM is the ability to combine functionalities of different software applications, to compare results between different analysis runs, and to share project materials across different disciplines and phases, where benefits can be achieved such as in detecting and avoiding clashes before the construction phase. After construction, project information captured in BIM can be utilized for building operation and maintenance purposes. BIM has revolutionized the construction industry and has become a hot topic of discussion in every organization in the AEC domain, due to the benefits that can be achieved when BIM is implemented (Hu et al., 2016).

A large number of participants from different disciplines, various teams and technologies involved, and the multi-phased and transitory nature of projects renders information management and collaborations in the AEC industry very challenging. Although BIM is designed to help with such collaborations, the lack of integration and interoperability is still causing problems in data transfer, which is considered as the main barrier for a wide adoption of BIM in the AEC industry (Hu et al., 2016). This leads to a bottleneck of productivity improvement among multiple disciplines in the AEC domain. BIM interoperability, therefore, is picking up significant interests in the last decades (Qin et al., 2011). Through full BIM interoperability, the work effectiveness and building quality can be enhanced, alongside with fewer expenses and assets (Liu et al., 2016).

The development of a range of BIM applications can significantly benefit from the improvement, enhancement, upgrade, and advancement of model-enabled interoperability, especially when unconnected spheres are linked together and offer paradigm shifts in thinking through new technology integration (Froese, 2002). Successful use of BIM tools in collaboration depends on whether the information produced by the various participants in different stages of the project can be successfully shared/exchanged through the entire building lifecycle.

The exchange of information in the AEC domain has always been an important but complex task. Users in various stages of a project need to interact with each other and exchange information throughout a project. Therefore, some important considerations for the use of BIM programs in designing a structure include choosing suitable platforms, which does affect the level of interoperability that can be achieved. During such considerations, in addition to the software's internal functions and features, data transfer and linkage protocols between different software must be taken into consideration as well (Pazlar & Turk, 2008).

In the structural engineering domain, building projects normally involve multiple engineers and consultants who may conduct structural analysis using different software platforms. The processes involved in structural analysis necessitate them to share various sets of data and information with each other. In a typical structural model, display of information from multi-disciplinary projects needs coordinating heterogeneous data under a shared standard. BIM-based structural models, typically, can be divided into two types - detailed models and analysis models. The detailed models encompass materials extracted from architectural models, geometric shapes of building elements, and section properties, etc. (Becerik-Gerber & Kensek, 2009). The analysis models, on the other hand, comprises of the information required only for structural analysis purposes, such as axis position, member size, and space layout. The benefits of using BIM for structural analysis lie in the fact that numerous modeling and analysis methods can be used to verify compliance of a proposed design with complex structural safety constraints, where the needed information can be provided by different participants at different stages.

Interoperability between different BIM software and different BIM processes is complex and diverse, which is directly related to the complexity of the software used in the processes and their input/output (Grilo & Jardim, 2010). Froese (2010) pointed out that the complexity of the processes can be reduced through a change in the management perspective to focus on the adoption of interoperable communication (Froese, 2010). A standard representation of technical data in the AEC industry will, therefore, facilitate the data exchange and thus improve interoperability. Industry foundation classes (IFC) is such a data representation standard that bears ISO certification (Dhillon et al., 2014). It is also practically an executable data scheme that underpins information dissemination of building and construction industry data (Namini et al., 2012). Because interoperability impacts the value of BIM in the AEC industry (Young et al., 2009). Theoretically, the best method of adopting BIM in the AEC industry is to use a common/central model at a position to receive information from all software analyses and make periodic updates/amendments to reflect changes in the material (Becerik-Gerber & Kensek, 2009). Practically, data sharing/transfer is at the core of BIM-based interoperability between various software analyses, which requires data to be well organized and standardized (Hunt, 2013).

There are three main paths for data sharing/transfer between BIM data analyses: direct link using native file, direct link using Application Programming Interface (API), and indirect link. The direct link using native file refers to internal data exchange using files that are native to a software suite, therefore needs no translator during the file exchange. This type of data transfer could exchange information with minimum error, and the transfer process is usually fast and straightforward. For example, direct link using native file is used in Autodesk Revit software suite, such as between Revit Structure and Robot Structural Analysis (RSA). Any information related to structural analysis can be directly defined in Revit Structure and transferred to RSA for analysis, because they share the same library and data definitions. The data definitions can further impose information need of the analysis. Although the direct link using native file is the best solution for internal interoperability within a software suite, its use is limited with software from different suites (Eastman et al., 2011). Direct link using API, however, allows the use of a temporary file exchange between software applications from different suites through a cooperation arrangement between companies who developed the applications. The advantages of this direct link is refelected in its capabilities, possibilities and its differences from other exchanges. This unique data exchange path enables software companies to provide better support of interoperability of their platforms with external applications, with interfaces to help read and write data in their native format. The protocol of data exchange is then determined by interested companies together depending on their respective needs and supplies. This is an active link because the collaborating companies maintain the exchange channel together during the development and maintenance of their applications, and address problems together that have been identified in previous versions (Eastman et al., 2011). Indirect link is the most flexible way to exchange data, because this method enables the transfer of data models between different software applications and between different company's software suites, utilizing an open data standard and format, such as a text file (IAI 2010a). Despite its popularity and importance, indirect link is challenged by multiple problems in the data exchange such as the loss of essential data and inconsistency between data source and target. For example, essential data in a structural design such as loads, boundary conditions and stiffness of materials may encounter loss during data exchange through indirect link (Eastman et al., 2011).

Effective collaboration between architectural design and structural analysis is an important part of the success of building design to save the potential time and cost in the required modifications otherwise. It is also an essential part of the overall collaboration process in an AEC project. This research focuses on investigating the interoperability between architectural design and structural analysis via the three different types of data transfer paths.

Objectives

This study has two main objectives: (1) to initially investigate the interoperability of BIM between architectural design and structural analysis through a data-driven approach, by empirically analyzing and studying structural models created in an architectural platform; and (2) to build up a robust structural analysis case consisting of an array of beams and columns that are firmly bounded together for use in future research as a benchmark.

This study will focus on testing the transfer of structural information such as material types, section dimensions, load, boundary conditions, position of analytical line, elastic modulus, and moment of inertia.

This study will investigate the three types of paths for data transfer between architectural and structural models (Figure 1): (1) direct link using native file, which is the direct link between software programs from the same provider. The authors selected Revit for architectural design and RSA for structural analysis; (2) direct link using API, which is the data transfer with a BIM platform through its APIs. The authors selected Revit API interface, which can be accessed through programming languages such as C++ or C# (Eastman et al., 2011). This type of link is used, for example, between Tekla Structures and Autodesk Revit. In practice, companies create programs on C++ to access the API, which assures a smooth data flow process when exchanging data; and (3) indirect link, which is the indirect transfer of information through third-party software or methods/algorithms. Third party resources include data standards such as the CIMSteel Integration Standards (CIS/2), the Steel Detailing Neutral Format (SDNF), and the IFC. The CIS/2 and SDNF are preferable when dealing with data exchange for steel structures, whereas IFC is one of the most widespread data standards for information exchange in the building and construction industry in general. Indirect link is the most common process of data exchange through models between software by different vendors. In this study, the indirect link is investigated with a special focus on the use of IFC data. During the investigation of the three types of data transfer paths, the loss of data critical for structure analysis will be identified. Based on the study results and findings, new methods and algorithms can be developed to help improve the interoperability of BIM between architectural design and structural analysis.

Figure 1: The three types of data transfer paths.

Architectural and Structural Model

BIM data coming from architecture model has a variety of information, some of which is not needed in structural analysis. The structural model only requires information pertaining to structural analysis, including the geometry of the structure, location of the members in a coordinate system set by the software, the types of materials and their properties. Load types and load cases, and boundary conditions can also be part of the exchanged data with an architectural model. However, the structural engineers usually prefer adding them in the structural model directly because they are more related to the structural specialization (Tamas et al., 2016). Figure 2 illustrates the differences between an architectural model and a structural model of a simple concrete frame.

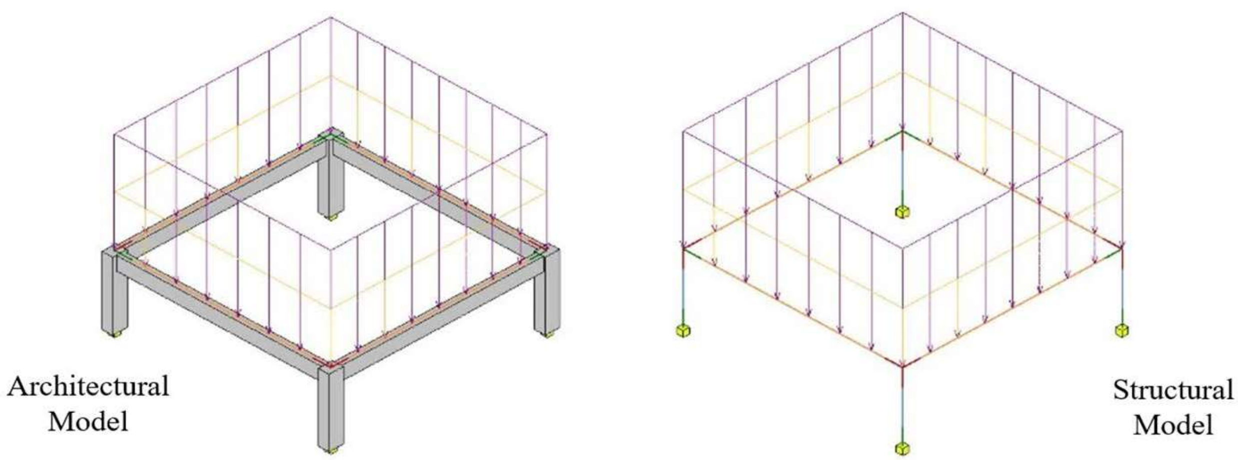

Figure 2: Architectural and structural model.

Case Study

This case study was aimed at investigating how BIMs resulting from architectural design could be used in structural analysis, and analyzing the three types of data transfer paths in terms of their ability to maintain data integrity. The case study consisted of a multi-story concrete building, with live and dead loads uniformly distributed on the beams. The major structural components included the exterior and interior columns (dimensions are 12 *in.* * 24 *in*. and 12 *in*. * 30 *in*., respectively), beams (12 *in*. * 18 *in*.), and isolated footings (72 *in*. * 72 *in*. * 18 *in*.). Note that the ends of columns connected with isolated footings were included as fixed ends. The BIM model was created using Revit 2018 (Figure 3).

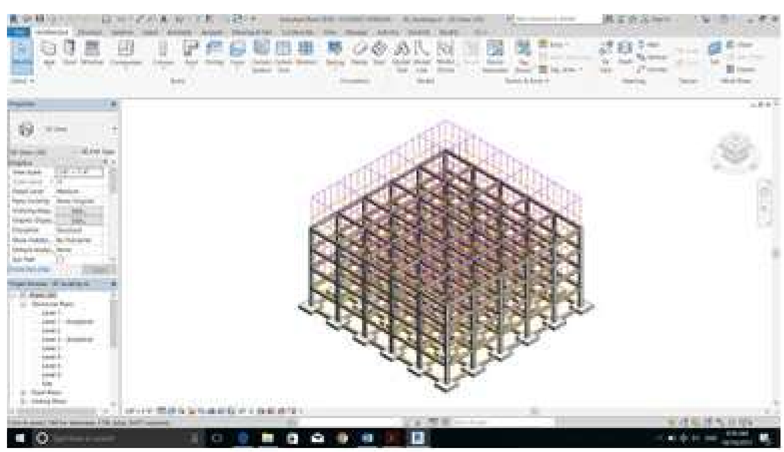

Figure 3: Case study BIM model.

Direct Link Using Native File

The direct link is a data transfer between different software from the same software provider. The case study model was created in Revit and then exported via a direct link to RSA. The procedure of data transfer is shown in Figure 4. Information transferred included section properties, geometries of building elements, their material properties, loads, and boundary conditions.

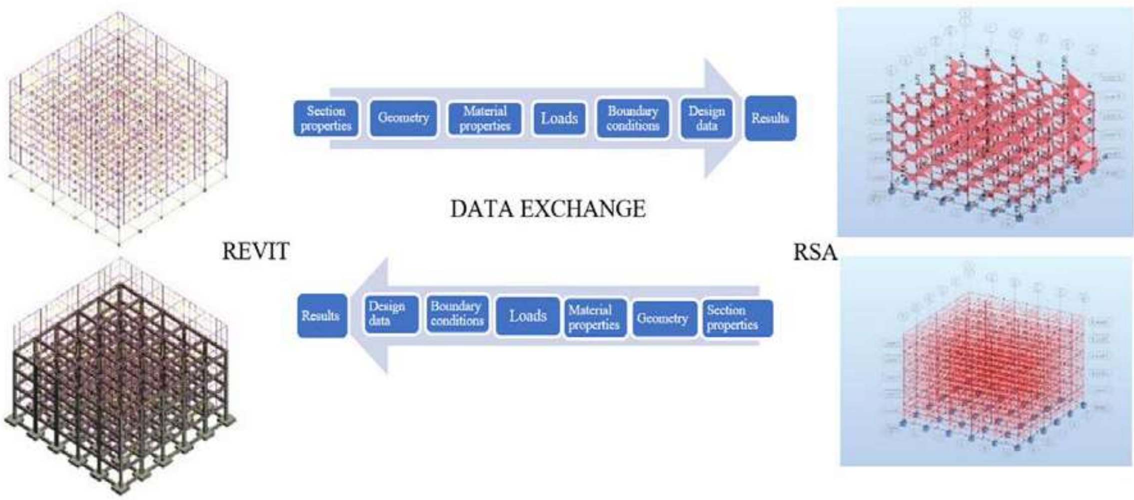

Figure 4: Direct link using the native file.

Direct Link Using API

Structural engineers that work on CSI programs have created CSIRevit link that can be used to exchange BIM data between Revit 2018 and ETABS 2015 or later, SAP2000 v17 or later, and SAFE 2014 or later. This link was created through the Revit API. The link supported different workflows: exporting from and importing to Revit to create a new model or updating existing ETABS, SAP2000 and Safe models (Computers and Structures, Inc., 2017). This link aimed to address the problem of collaboration between architectural designers and structural engineers and had improved interoperability between the two disciplines. The procedure of data transfer is shown in Figure 5. The advantage of a direct link was that it was usually efficient and effortless to transfer data. In addition, the direct link was working in two directions, both from Revit to RSA and CSI programs and the other direction. This bidirectional data compatibility was of significant importance because architects might need to make changes in Revit model according to structural analysis results of their designs. The Information transferred was the same as in the direct link using the native file. The structural analysis results in the three CSI programs using the transferred data were mostly successful (Figure 6).

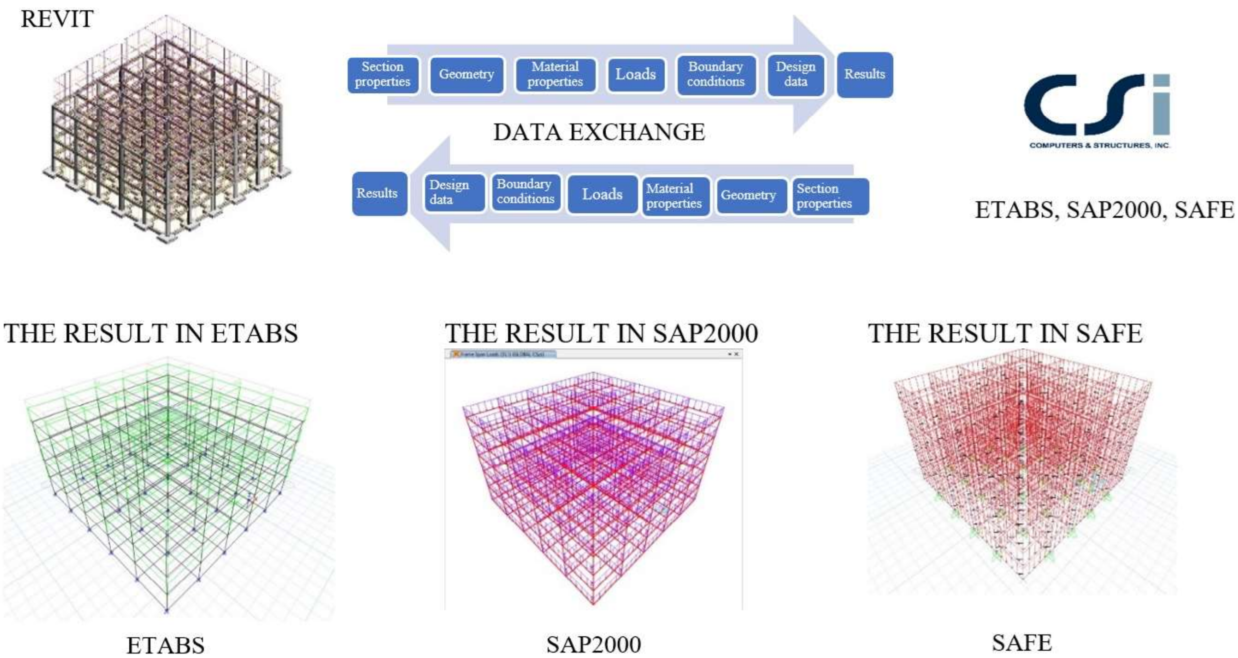

Figure 5: Direct link using API - CSIRevit.

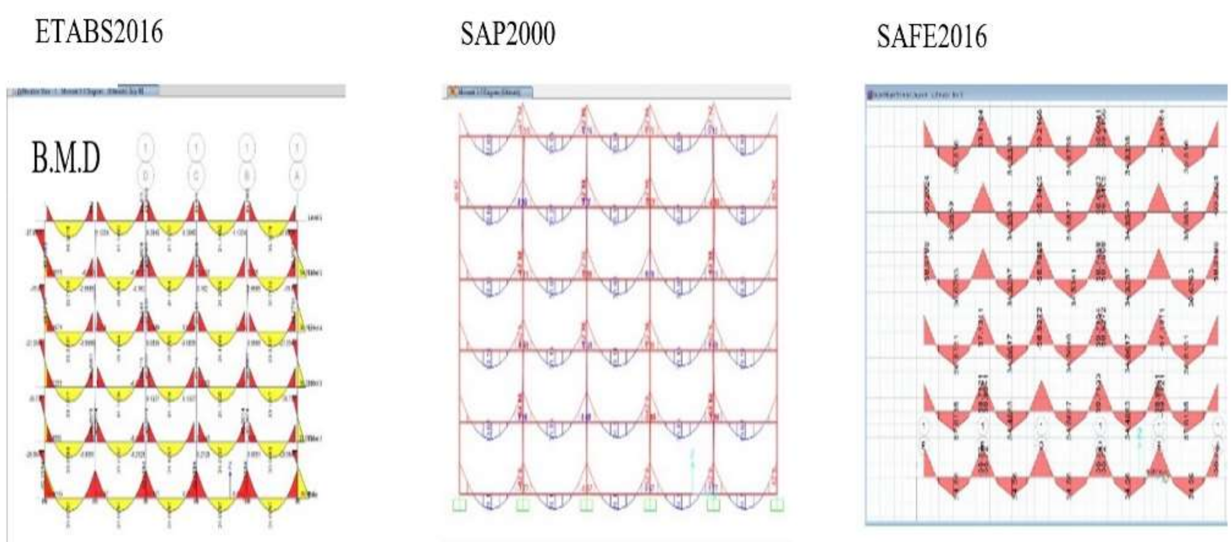

Figure 6: Direct link using API - analysis results using transferred data.

Indirect Link Using IFC

For indirect link data transfer using IFC, the experiment was set up for exchanging data from Revit to ETABS 2016 and SAP2000, via an IFC file. SAFE was not used because it did not support IFC input at the time of the experiment. The procedure of data transfer is shown in Figure 7.

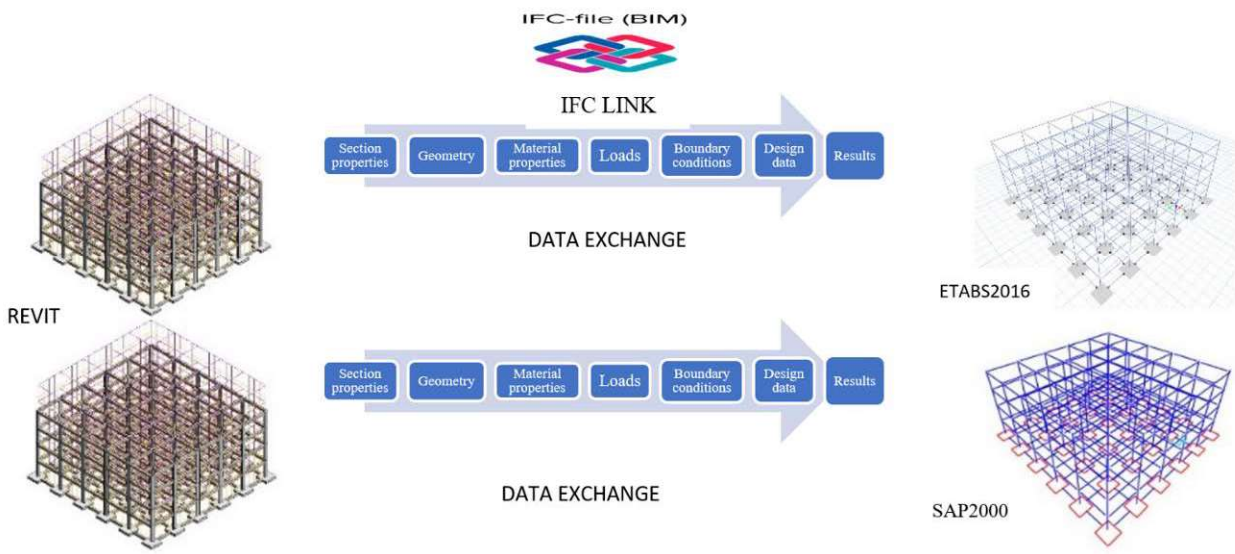

Figure 7: Indirect link through an IFC file.

Results and Analysis

The results of data transfer in all three types of paths are shown in Table 1. While information missing was observed in all cases, the data transfer via the indirect link showed more information missing than that via direct links. In addition, all types of boundary conditions in Revit (pinned, roller, and fixed), when they were being transferred to ETABS and SAFE programs, were treated as pinned. It was noted that the values of multiple material properties such as elastic modulus (E), shear modulus (G), Poisson's ratio and thermal expansion coefficient were changed during the data transfer via the indirect link, whereas in direct link only the value of thermal expansion coefficient was changed. Self-weight load and section properties were the main information missing during data transfer through direct links, because they did not already exist in the Revit program. However, boundary conditions were also missing when transferred to SAP2000 using direct links through API. The main problem of data transfer using the indirect link through IFC, in addition to missing self-weight load and boundary conditions, was the missing of loads and load combinations. Model instability and nonpositive stiffness properties were also observed in data transfer results through IFC. Because the position of the analytical line was undefined in the IFC file, the IFC file relied on the actual lengths of the building elements for the imposition of an analytical line, which caused a loss of connections between the elements.

Two main problems of information exchange between architectural design and structural analysis programs that were discovered through this experiement, therefore, were the loss of information and value changes. However, the impact of such problems on structural analysis may vary. In other words, not all of the missing data or value changes would affect the analysis, such as the data of section area and moment of inertia. The structural analysis software will be able to calculate them on the fly or assume values to use for part of the missing information and detect inappropriate values based on existing relationships between model parameters. But there are irreplaceable information in structural analysis without which the analysis could not be successfully conducted. For instance, material types, element lengths, section dimensions, loads, boundary conditions, positions of the analytical line, and elastic modulus all belong to such irreplaceable information.

Table 1

Comparison between three path types for BIM interoperability based on case study examinations

Data transfer path	Software	Results
Direct link through native file	from Revit to RSA	1- self-weight load & section properties not already existing in Revit program (missing) 2 - thermal expansion coefficient (value changes)
Direct link through API	from Revit to ETABS	1- self-weight load & section properties not already existing in Revit program (missing) 2 - thermal expansion coefficient (value changes) 3 - footing connections all treated as pinned except for isolated footing (fixed) (type changes)
	from Revit to SAFE	1 - self-weight load & section properties not already existing in Revit program (missing) 2 - thermal expansion coefficient (value changes) 3 - all footing connections treated as pinned
	from Revit to SAP2000	1 - self-weight load & section properties not already existing in Revit program (missing) 2 - thermal expansion coefficient (value changes) 3 - boundary conditions (missing)
Indirect link through IFC	from Revit to ETABS	1 - self-weight load & section properties not already existing in Revit program (missing) 2 - loads & load combinations (missing) 3 - material property data such as elastic modulus (E), shear modulus (G), Poisson's ratio and thermal expansion coefficient changed (value changes) 4 - length of the analytical line not defined 5 - all footing connections treated as pinned
	from Revit to SAP2000	1 - self-weight load & section properties not already existing in Revit program (missing) 2 - boundary conditions (missing) 3 - loads & load combinations (missing) 4 - length of the analytical line not defined 5 - materials property data such as elastic modulus (E), shear modulus (G), Poisson's ratio and thermal expansion coefficient changed (value changes)

Conclusions, Limitations, and Future Work

The development of BIM has led to the establishment of open and neutral data schemas such as industry foundation classes (IFC), which intended to streamline the flow of information between BIM software in various disciplines. Some BIM software applications support exportation and importation of various formats while others do not. However, most BIM software (if not all) have certain levels of compatibility with the IFC standard. In this paper, the authors have analyzed the interoperability between architectural design and structural analysis through BIM. Three types of data transfer paths were evaluated, namely, direct link using native file, direct link using API, and indirect link through IFC. The experiment showed that all the three types of paths involved a certain level of information missing and value changes, where the indirect link through IFC showed the most information missing and value changes. Therefore, BIM software developers are recommended to build in full IFC support in their BIM platforms to enable the use of direct link, including complete information importation and exportation. Future work is also recommended to look into the causes of information missing and value changes, and develop methods to mitigate it in the paths of direct link through API and indirect link through IFC. Solving this missing information and value changes issue is an important first step to solve all interoperability challenges.

One main limitation of this study is acknowledged: the experiment was only conducted on one project model. While it could be sufficient to help identify certain interoperability problems, the scenario may be different when different types of structural models are used. Therefore, more testing using different types of structural models is needed to further verify the findings in this paper. As part of future work, the authors plan to repeat the experiment on more structures of different types (e.g., steel structure, composite structure, timber structure) and complexities, as well as look into the causes of the information missing and value changes problems and develop methods/algorithms to mitigate them.

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